The *StarLight* Metrology Subsystem

Serge Dubovitsky[1], Oliver P.Lay[1], Alexander Abramovici[1]
James G. Hawley[2], Andreas C. Kuhnert[1], Jerry L. Mulder[1], and Cheryl G. Asbury[1]
[1] Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr. m/s 301-451, Pasadena, CA, 91109, USA, 818-345-9796 e-mail: serge.dubovitsky@jpl.nasa.gov
[2] Lockheed Martin Advanced Technology Center
B-201, L-923, 3251 Hanover St. Palo Alto, CA 94304-1191, USA

Abstract— We describe a metrology subsystem for NASA's *StarLight* mission, a space-based separated-spacecraft stellar interferometer. It consists of dual-target linear metrology, based on a heterodyne interferometer with carrier phase modulation, and angular metrology designed to sense the pointing of the laser beam. The dual-target operation enables one metrology beam to sense displacement of two targets independently. We present current design, breadboard implementation in a stellar interferometer testbed of the Metrology Subsystem and the present state of development of flight qualifiable subsystem components

1. THE *STARLIGHT* MISSION

NASA's *StarLight* mission, scheduled for launch in 2006, will be the first formation-flying optical interferometer in space. The goal of the 6-month mission is to demonstrate the technology that will be needed for future astrophysics missions, such as the Terrestrial Planet Finder. The two spacecraft configuration (Fig. 1a) has a projected baseline that varies between 30 and 125 m as the separation is increased from 40 to 600 m. The collector spacecraft relays the incoming starlight to the combiner spacecraft, where it is combined with light that enters the combiner directly. To obtain an interference pattern, the two paths from the star to the beam combiner must be equalized to a fraction of a micron. A 14 m fixed delay line on the right side of the optical path (Fig. 1b) compensates for the gross geometrical offset in path length. A variable delay line on the left side of the Combiner optics is used to actively compensate for the small motions of the spacecraft. Further details can be found in references [1, 2]. The metrology system serves four primary purposes: (1) Measure the rate of change of the separation between the spacecraft, i.e. the range rate. A separate RF sensor is used to measure the absolute range. (2) Measure the position of the variable delay line. (3) Measure any high frequency jitter in the optical path lengths through the system. (4) Provide a sensor to ensure that the left boresight of the Combiner is always pointed at the center of the Collector optics. The Linear Metrology system addresses (1), (2), and (3); the Angular Metrology system addresses (4).

This paper describes the current design and breadboard implementation of the Metrology Subsystem in separated-spacecraft stellar interferometer testbed and the present state of development of flight qualifiable subsystem components

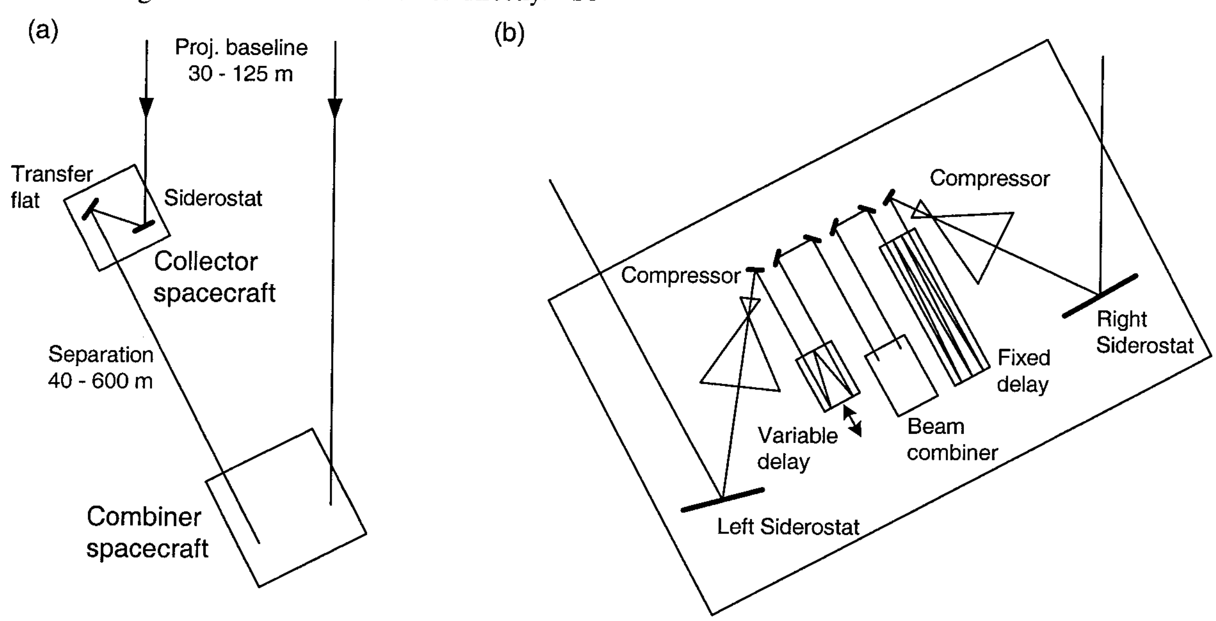


Figure 1. (a) Schematic formation configuration. (b) Combiner optics schematic.

2. Metrology Subsystem Functionality

StarLight metrology system is based on an optical heterodyne interferometer gauge. It uses changes in an optical phase of a laser beam propagating between fiducial and target reflectors to detect linear disturbances in an optical pathlength between the two targets. A quad-cell-like device is used to detect disturbances in the pointing of the laser beam. A top-level functional block diagram of the Metrology subsystem is shown in Figure 2.

Metrology Source, containing a laser and associated optoelectronics, supplies properly prepared optical beams to Metrology Optics. Metrology Optics are used to route the left and right laser beams between the fiducial point F and the three targets: A, B and C. On the right side metrology senses optical pathlength disturbances inside the combiner spacecraft, Right Intra-Combiner disturbances. On the left side the Metrology independently senses the pathlength disturbances inside the combiner spacecraft (Left Intra-Combiner disturbances) and pathlength changes due to spacecraft separation (Inter-Spacecraft disturbances). A Metrology Pointing Sensor determines the shear of the beam relative to sensor's center and therefore senses disturbances in the beam pointing. The centroid information, Δx and Δy, is transmitted back to the Combiner spacecraft via an RF link.

The Metrology can be broken into two functional elements: Linear Metrology and Angular Metrology. Each is sensitive to the measurands shown in Table 1. The metrology measurands are then used by the Instrument to calculate quantities shown in the Metrology purposes column.

Table 1. Connection between Metrology functional elements, measurands, and purposes.

Metrology purposes	Measured disturbance	Measurand	
(1) measure the range rate	Left Inter-Spacecraft disturbances	AF-BF	Linear Metrology
(2) measure position of the variable delay line	Left Intra-Spacecraft disturbances	BF	
(3)measure high frequency jitter in the optical path lengths through the system.	Inter-Spacecraft disturbances and Right Intra-Combiner disturbances	AF, BF, CF	
(4) measure Combiner boresight pointing	Pointing Disturbances	Δx, Δy	Angular Metrology

3. Metrology System Implementation

The schematic of the StarLight metrology system implementation is shown in Figure 3. The Right Intra-Combiner Metrology is a standard heterodyne metrology gauge. On the left side the dual-target architecture enables a single gauge to serve as both Left Intra-Combiner Metrology

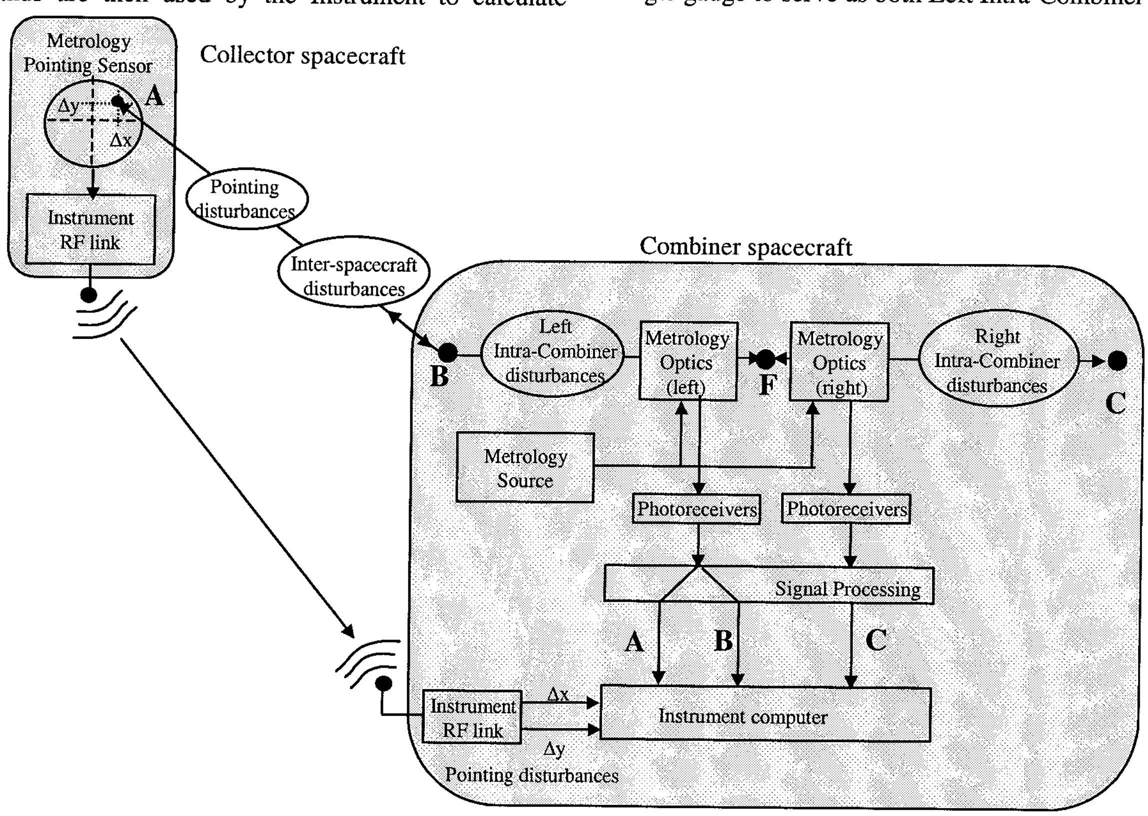


Figure 2. Top level functionality of Metrology subsystem

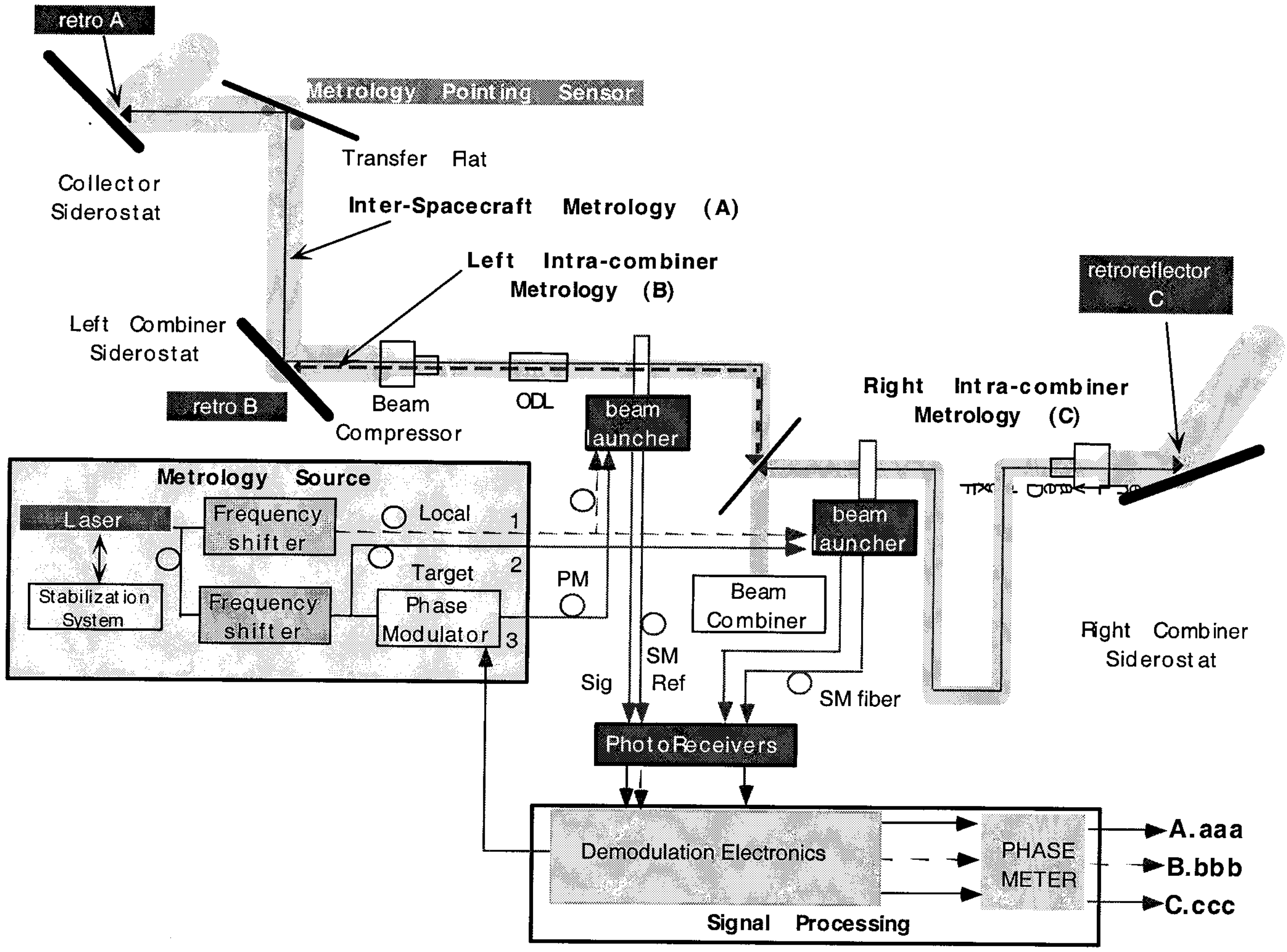


Figure 3. Metrology subsystem implementation

and Inter-Spacecraft Metrology. The dual-target concept is described in Section 4.1

A narrow-linewidth fiber coupled laser is used as the optical source for the interferometer. It is split into the Local and Target paths. Frequency Shifters are used to create a frequency difference between the two paths equal to the desired heterodyne frequency (10 kHz). Two frequency shifters are used, because existing optical frequency shifters operate at multi-megahertz frequencies, whereas we desire a kilohertz heterodyne frequency. A Phase Modulator in the Target path is used to enable the dual-target operation on the left side. The inherent laser frequency stability is not sufficient to enable the required 11-nanometer resolution at a 600 meter target distance and so we use an external frequency Stabilization System. The Metrology Source, consisting of the above components, is then connected via polarization maintaining fibers to the Beam Launchers. The Beam Launchers collimate the fiber output and direct the Target metrology beam along the boresight of the stellar beam. The metrology beams are returned back to the beamlauncher by the retroreflectors. At the Beam Launcher the returning Target beams are combined with a Local beam in a single mode fiber and taken to the remotely located photoreceivers. The electronic signals are subsequently demodulated into three independent heterodyne signals and the desired heterodyne phase shifts are measured by the Phase Meter. The three outputs of the Phase Meter are used to detect changes in the optical pathlength to the three targets A, B, and C.

Metrology Pointing Sensor is implemented as an Intensity Gradient Detector mounted on the Collector Transfer Flat. It is essentially a quad-cell consisting of four separated photodetectors.

4 Linear Metrology

Linear part of the StarLight Metrology is implement as a heterodyne interferometer with dual-target capability. The dual-target concept, described in the subsequent section, is an novel interferometer architecture [3] developed at JPL in response to the needs of the StarLight mission. The parabolic geometry of the StarLight stellar interferometer [4] demands that the intra-combiner and inter-spacecraft pathlength disturbances on the Left side be known independently. Dual-target architecture enables us to measure two targets with a single gauge.

4.1 Dual Target Metrology Concept

The StarLight linear metrology system operates at 1320 nm, with independent gauges to monitor the left and right optical paths through the instrument.
The right gauge is a standard heterodyne metrology gauge. The left gauge monitors both the path internal to the combiner (from the beam combiner out to the left combiner siderostat) and the external path (from the left combiner siderostat to the collector siderostat). A novel phase modulation scheme allows us to separate the signal returns from two retro-reflectors, one located near the left combiner siderostat, the other on the collector siderostat (Fig. 1b).
The principle of operation is as follows. In a standard heterodyne metrology gauge, the *target* beam that propagates along the path to be measured, is given a frequency shift f_{het} with respect to the *local* beam. The two beams interfere at the photodetector producing a sinusoidal voltage output whose phase changes by 2π radians when the optical path length is changed by one optical wavelength (Fig. 4a). The phase of this *unknown* sinusoid is measured against a *reference* sinusoid. If phase modulation at frequency f_{pm} ($> f_{het}$) is now added to the target beam, the photodetector output resembles Fig. 4b.
The original heterodyne waveform can be recovered by mixing (b) with a sinusoid at f_{pm} (c) and removing the high frequency mixing products. This process is *demodulation.* The amplitude of the resulting waveform depends on the phase relationship between (b) and (c): if they are in phase, the demodulated output has maximum amplitude (Fig. 4d); if they are in phase quadrature, the demodulated output is zero (Fig. 4e).
These properties can be used to isolate the returns from two retroreflectors (A and B) offset in range by Δx along the same path. The B retroreflector assembly is partially transmitting. Choosing a phase modulation frequency $f_{pm} = c\ /\ (8\Delta x)$ ensures that the photodetector output waveforms from A and B are out of phase by 90 degrees. This output is split equally into two channels, 1 and 2. The phase of the demodulation waveform for channel 1 is chosen to be in phase quadrature with the return from B; the B return is nulled out, leaving the demodulated waveform from A. Similarly, the channel 2 output is the demodulated signal from B. The phases of these two waveforms are then measured separately against a reference waveform, as in the case of standard heterodyne metrology.
This system, shown in Fig. 5, has been successfully tested in the lab, and an isolation of 60 dB has been demonstrated between the two channels, i.e. the demodulated voltage amplitude from a single retro-reflector can be suppressed by a factor of 1000. The phase modulation frequency is 62.5 kHz for a spacecraft separation of 600 m, rising to 940 MHz for the shortest configuration with 40 m separation. This is sufficient to meet the 10 nm performance requirement for the StarLight mission. The dual target metrology is described in more detail in reference [3]. The technique also suppresses the self-interference error due to polarization leakage [5] .

4.2 Linear Metrology Components

We are currently working on developing components and integration techniques that will allow us to implement a space qualified version of the system. To increase the system reliability we chose to interconnect most of the components using polarization maintaining fibers[6]. Each component is pigtailed with input and output fibers that are fusion spliced together. Fusion splices have negligible loss and polarization degradation. Fiberoptic interconnects greatly simplify the testing and integration process by completely removing any need for inter-component alignment, significantly simplify the space-qualification process, and save weight and size compared to a stable optical bench and mounts. Even for laboratory use, fiberoptic integration leads to much lower integration costs, especially in terms of time, pain and suffering, although the cost for individual components may be higher.
Subsequent sections describe each of the components in its current state of development.

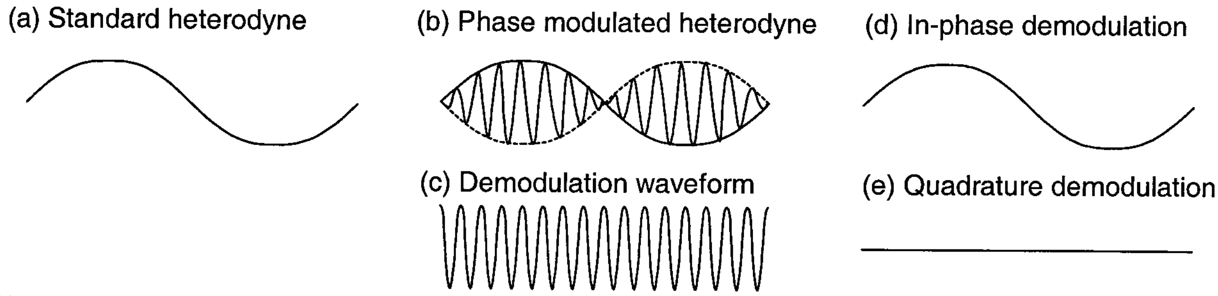


Figure 4. Modulation scheme for dual target metrology.

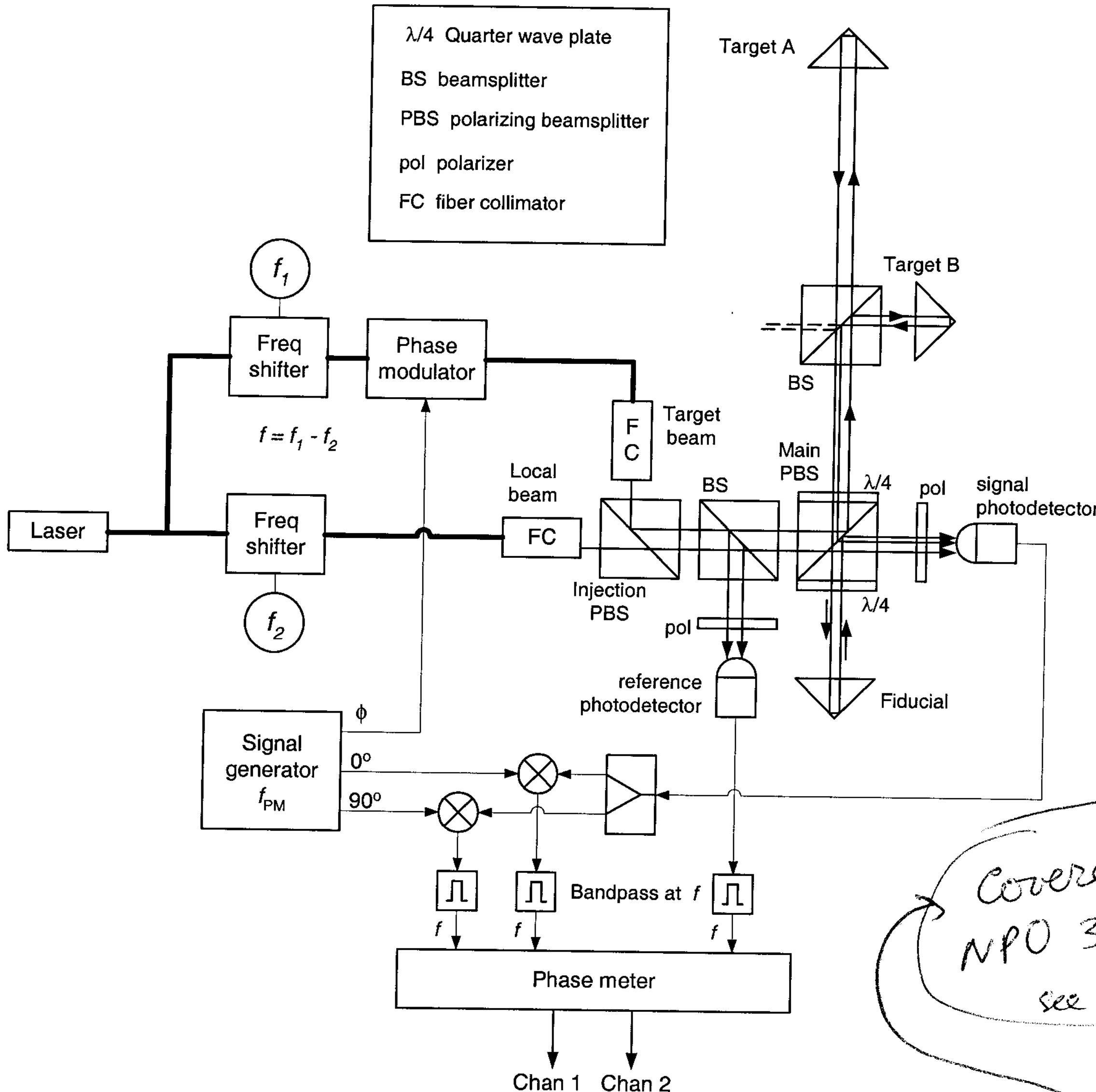


Figure 5. Implementation of the dual target metrology system

Covered by NPO 30353. see attached.

4.2.1 Laser

The laser for the StarLight metrology system needs to satisfy both rigorous functional and environmental requirements. In particular, the wavelength is required to be greater than 1.1 µm so that metrology light does not contaminate the visible starlight signal. The laser must provide high optical power (> 200 mW) and its frequency characteristics must be such that optical frequency noise can be kept below 100 Hz/root(Hz) between 10 and 1000 Hz. If the laser is not quiet enough on its own, this can be obtained by locking the laser to an external cavity, i.e. the laser must be tunable.

We chose a Nd:YAG Non-Planar Ring Oscillator (NPRO) laser operating at 1.32 um wavelength as the baseline laser for the metrology system. The testbed demonstrations have been implemented with commercial lasers from Lightwave Electronics Corp. The flight version of the system requires much greater reliability and lifetime. We have therefore, with support from Lightwave Electronics, developed a completely re-designed version of the NPRO laser, with laser welding of all critical-alignment components and a drastic reduction of the internal optical paths [7]. Another innovation is that the pump light is delivered to the Nd:YAG crystal via a multimode fiber through a specially designed ferrule that accommodates up to three pump diodes.*The ability to pump a single crystal with three diodes greatly enhances the reliability and lifetime of the laser and/or enables high power output.

For example, the reliability (probability of success)of a single laser diode still operating, using an MTBF (mean time between failure) of 10^5 hrs after a 1.5 yr total lifetime (0.5 yr, plus 1 yr testing) is 0.977. This is probably inadequate for a single component, given that there are many components to factor in for the total payload. The laser source reliability can be improved by adding more diodes

operating either in parallel (all on) or in a standby configuration. (one on at a time)
The parallel reliability equation as a function of time is given by[8]:

$$R(t) = 1 - (1 - \exp(-\lambda t)^m$$

where m is the number of parallel, identical components, and l is the inverse of MTBF. A sample calculation using the previous input parameters, and 3 diodes, yields a reliability of 0.998 which is far better than one diode. The reliability of 3 parallel pumps operating in a standby configuration is given by[8]:

$$R(t) = \exp - \lambda t \left[\sum_{r=0}^{r=m-1} \frac{(\lambda t)^r}{r!} \right]$$

The calculated standby reliability for the same conditions as before is slightly better, 0.9996. This does not take into account the switch required to divert from one diode pump to another.
With all three pump lasers turned on we were able to obtain 300 mW output at 1319 nm wavelength from our first multi-pump breadboard unit shown in Figure 6. We are working on increasing pumping efficiency and expect to be able to get even higher powers. We are still evaluating the best configuration based on pump vendor data and future tests.

4.2.2 Frequency Stabilization System

Currently our free-running lasers do not meet the frequency stability requirements of the mission (100 Hz/root(Hz) between 10 and 1000 Hz.), and an external frequency stabilization system is used. Because we need only a modest improvement in the frequency stability, we plan to use a simple transmit/reflect architecture in which the laser frequency is locked to the side of the cavity resonance peak [9].
The frequency stabilization system measures the transmitted light portion of a Fabry-Perot cavity and compares it to a stable reference voltage to generate the feedback signal. The principle is shown in Figure 7. This signal is controlling the laser frequency using the laser PZT ("fast") and crystal temperature ("slow") actuators, therefore keeping the light level on the photo detector constant. According to Figure 7 this is equivalent to keeping the laser frequency stable. Because this system measures the transmitted light level it is sensitive to laser power fluctuations. One remedy to this problem is to monitor the reflected light from the cavity as well and use the ratio transmitted/reflected as the sensor signal.

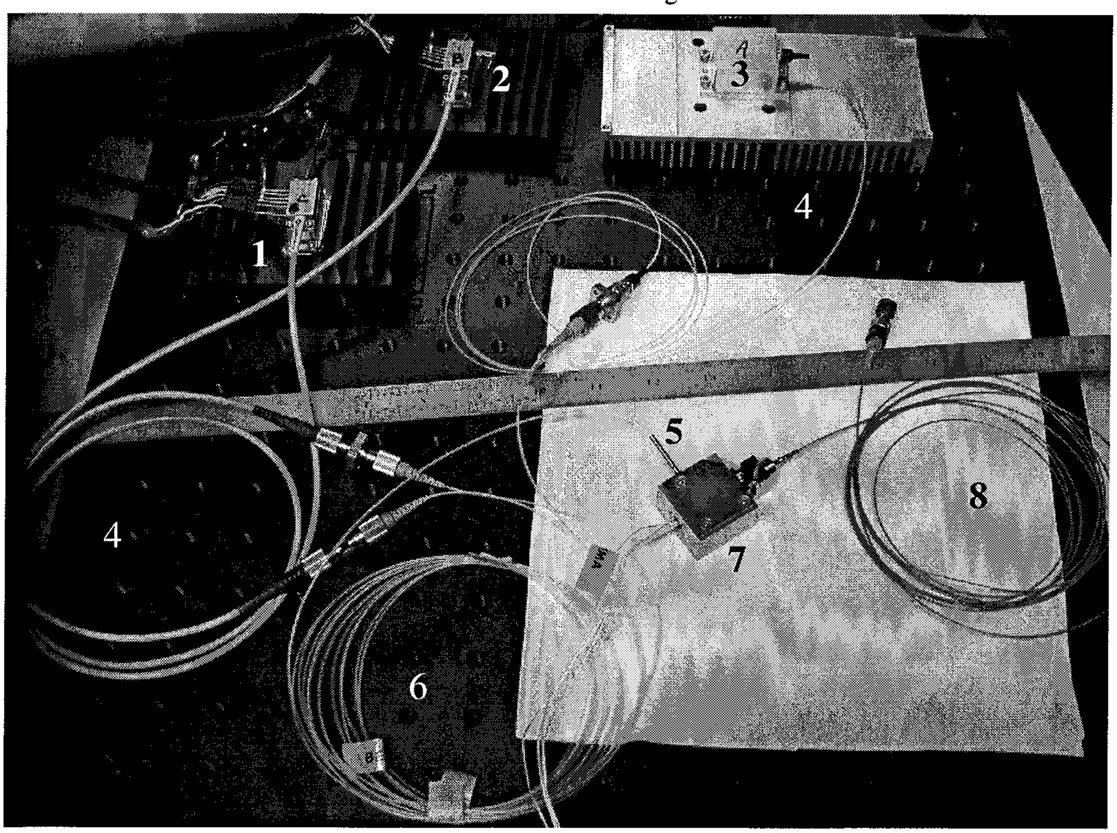


Figure 6: Multi-pump laser breadboard: 1,2,3-pump lasers (808 nm), 4 – pump lasers multimode output fibers; 5-Multi-Pump Fiber Ferrule (MPFF); 6- three fiber bundle of the MPFF; 7- laser welded Nd:YAG NPRO laser head; 8 – metrology laser output fiber (1319 nm)

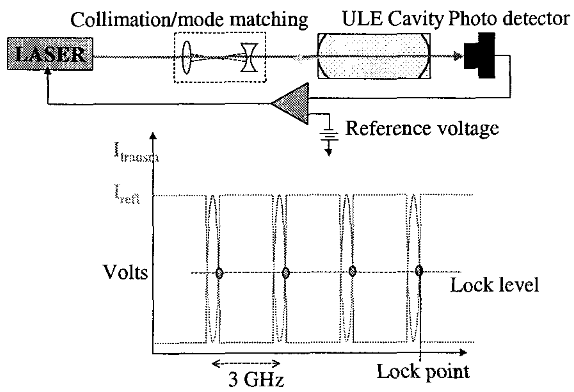


Figure 7: Illustration of transmission-lock concept

The frequency noise measurements were done by beating the stabilized laser light with the light from a second laser that was frequency stabilized using the Pound-Drever-Hall stabilization[(a)] [10]. We used two methods to measure the residual frequency noise, a frequency discriminator based on a delay line [11] and a Time-Frequency analyzer (HP5371A). The results of the frequency discriminator measurements are shown in Figure 8, they do agree well with the data taken with the Time-Frequency analyzer.

4.2.3 Frequency Shifters

The function of the frequency shifters is to change the optical frequency of input light by a well defined amount. In the laboratory acousto-optic modulators (AOM), also known as Bragg cells, are usually used for this purpose. For the flight design we've investigated integrated optics Acousto-Optic Tunable Filter (AOTF) as a frequency shifter, because of the inherent robustness of the integrated optics components [6]. These units, developed by commercial companies for telecommunications applications, performed well, but unfortunately are no longer available. We therefore plan to implement the Frequency Shifter using a bulk AOM pigtailed with polarization maintaining fibers using laser welding technology developed for the Metrology Laser.

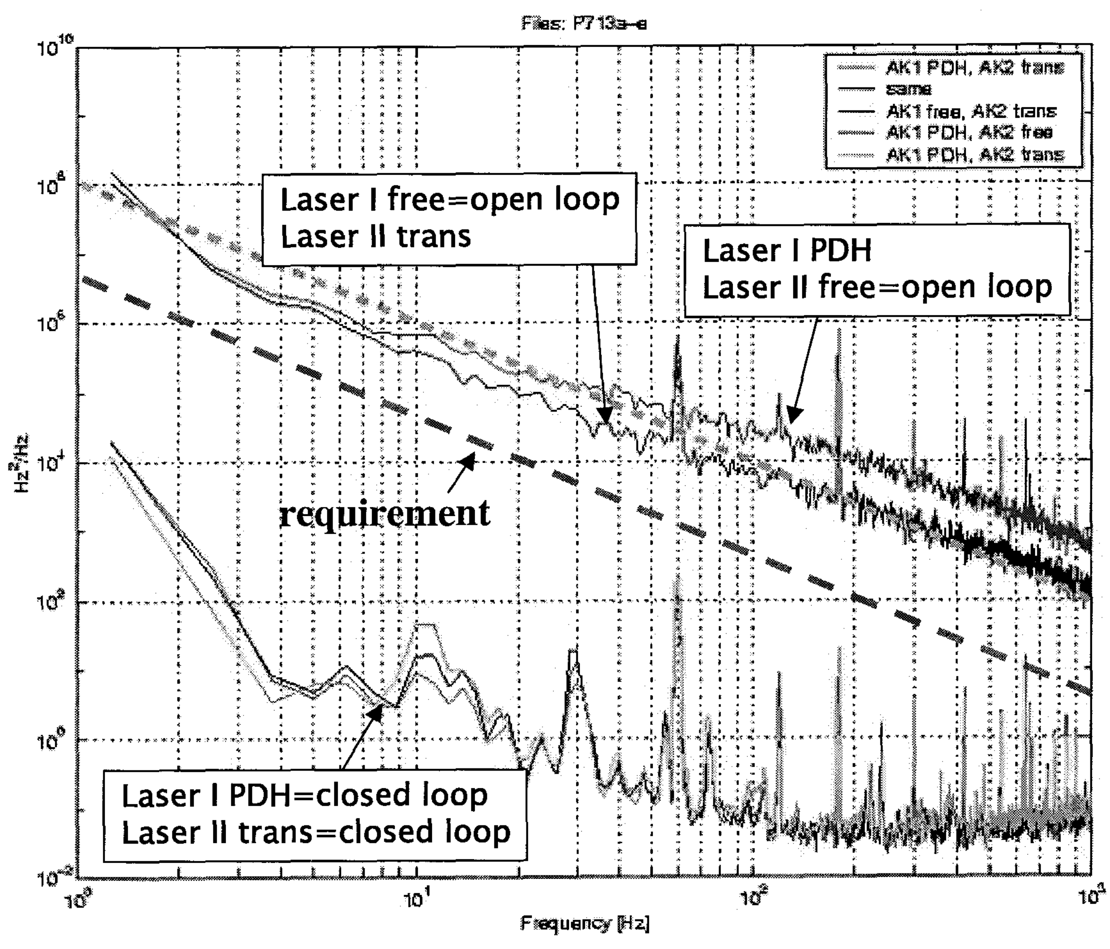


Figure 8. Experimental results. Frequency noise is measured by beating the output of the laser under test with another laser.

4.2.4 Phase Modulator

We are currently using commercial-off-the-shelf (COTS) integrated optics phase modulators built to the telecommunications providers standards. Some of the telecom standards appear to be more stringent than our flight requirements. We are working on developing a flight qualification approach for these COTS parts.

4.2.5 Metrology Optics

Metrology Optics consist of Beam Launchers, used to insert metrology beams into the starlight path, retroreflectors, used to return the metrology beams from fiducial and target points, and photoreceivers, used to detected the optical signals and convert them to electronic signals.
The metrology beam occupies the inner 2 cm of the fully expanded 12 cm aperture. This beam size is reduced by a factor of 4 in the region between the compressors and the beam combiner, so that the metrology beam launcher injects the target beam within a diameter of 5 mm.
The target and local beams are distinguished by their polarization state; the target beam is s-polarized (i.e. out of the plane of Fig.5) and the local beam is p-polarized (i.e. in the plane of Fig.5). They are combined at the injection polarizing beamsplitter (PBS) and propagate to the Main PBS, with a small fraction of each diverted off to the reference photodetector along the way. At the Main PBS, the p-polarized local beam passes straight through, and the s-polarized target beam is reflected out into the combiner spacecraft optical train. A quarter-wave plate converts the linear polarization to right circular polarization (RCP). A beamsplitter and retro-reflector (Target B) return a fraction of the light that is used to monitor displacements within the left combiner optics; most of the light continues out to Target A located on the collector. On retro-reflection at the targets the RCP light is converted to LCP and propagates back to the Main PBS. A second passage through the quarter-wave plate converts to p-polarization which is transmitted by the Main PBS, gets converted to LCP, and then returned as RCP by the fiducial retro-reflector. This RCP is converted to s-polarization which is then reflected towards the signal photodetector by the Main PBS. A polarizer is used to mix the target and local beams prior to detection.
The collimators, polarizers, beamsplitter cubes and quarter-wave plates will be co-mounted on a beamlauncher assembly. The right-side metrology optics are identical to those on the left, except there only a single target retro-reflector is needed

4.2.6 Signal Processing

The signal processing electronics convert the electrical waveforms generated by the four photodetectors into three sets of displacement measurements: the left internal combiner path, the left external combiner path, and the right internal combiner path. The signal processing needed to implement the dual target metrology scheme for the left arm of the instrument is shown schematically in Fig. 9. The signal generator is likely to be implemented as a programmable direct digital synthesizer, generating sinusoids of the specified frequency, phase and amplitude. The radio-frequency (RF) section consists of a splitter, mixers for demodulation, amplifiers to boost the weak signals, and filters to remove unwanted spectral components. The phase meter is based on a JPL design [12] that times the interval between zero crossings of the signal and reference waveforms. One of the key design challenges will be to maintain an isolation of > 60 dB between the different channels.

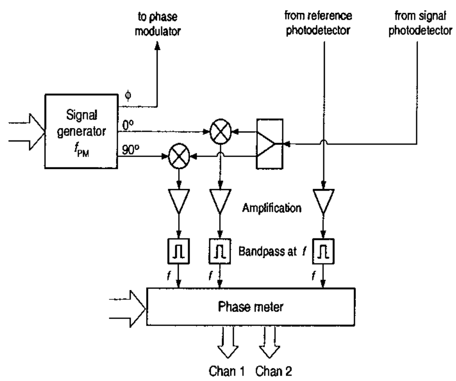


Figure 9: Schematic of signal processing electronics for left metrology gauges. Broad arrows represent a computer interface.

5 ANGULAR METROLOGY

The purpose of the angular metrology is to provide a sensor to ensure that the left boresight of the Combiner is always pointed at the center of the Collector optics. The Metrology Pointing Sensor is implemented as an Intensity Gradient Detector (IGD) shown in Fig. 10. It consists of four photodiodes mounted at the center of the Collector transfer flat (Fig. 1a), with a separation of 2 cm. The linear metrology laser light incident on the IGD from the Combiner has a Gaussian intensity distribution and nominally illuminates the photodiodes as shown in Fig. 10. When the metrology beam is centered on the IGD array, all the detectors see equal intensity and produce identical output signals. If the beam pointing changes on the Combiner it will be observed as a beam shear at the Collector, and the outputs of the IGD detectors will no longer be balanced. By differencing the detector outputs pair-wise and normalizing by the pair-wise sum we can determine the direction and magnitude of the beam displacement from the Collector optical axis.

The photocurrents from the four photodiodes can be used in a variety of ways to infer the position of the beam. One particularly convenient set of variables consists of Δx and Δy defined in fig. 11. The advantage in using these variable

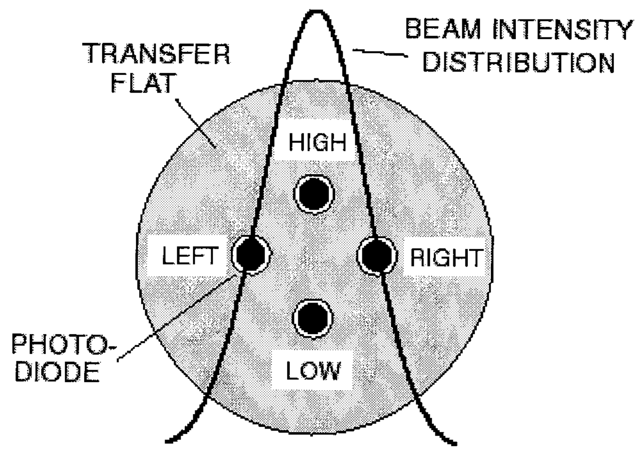
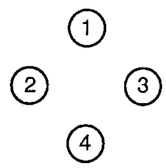


Figure 10. IGD photodiode pattern and beam intensity distribution with respect to the Transfer Flat

$$\Delta X = \frac{I_2 - I_3}{I_2 + I_3}$$

$$\Delta Y = \frac{I_1 - I_4}{I_1 + I_4}$$



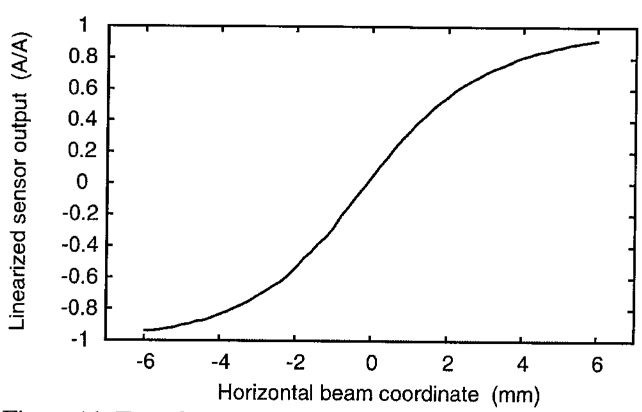


Figure 11. Transfer curve of the IGD

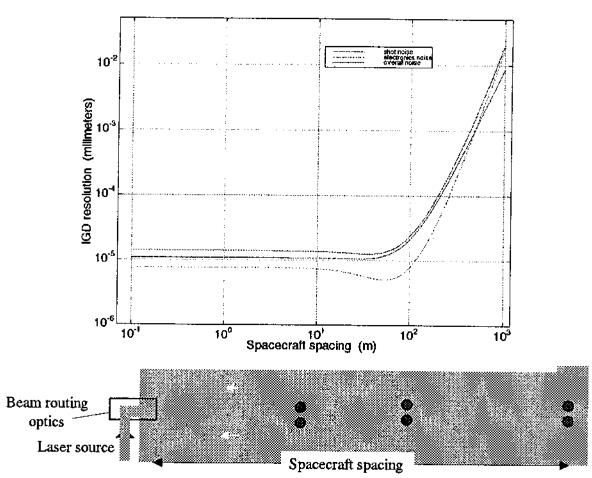


Figure 12. IGD shear resolution as a function of spacecraft separation

stems from the fact that their functional dependence on the corresponding beam coordinates is particularly simple and can be well approximated well using a simple odd-order polynomial, e. g. a cubic. This simplifies the calibration of the sensor.

The spatial resolution of the sensor depends on the slope of the curve in Fig. 11 and on the unavoidable noise contributions to the photocurrents.

The slope of the variables Δx and Δy versus the corresponding beam coordinate depends on the size of the pattern defined by the four photodiodes, which is fixed, and on the beam diameter, which varies with the distance from the beam launch point, see Figure 12. The two main noise contributions are:

- Photon shot noise, which is proportional to the square root of the photocurrents. The photocurrents in turn are proportional to the amount of light incident on the photodiodes, which is a function of distance from the beam launch point.
- Electronics noise is generated by dark current at the photodiodes an by the preamplifiers. This contribution does not depend on position along the beam.

Knowledge of the inter-spacecraft distance enables us to convert the error in transverse beam position measurement into a pointing error signal for the combiner siderostat. The noise contributions discussed above and the total resulting limitation in sensor resolution are shown in Fig. 7 in units of beam pointing error. As the plots show, the resolution of the pointing sensor is adequate for *StarLight*, with sufficient margin.

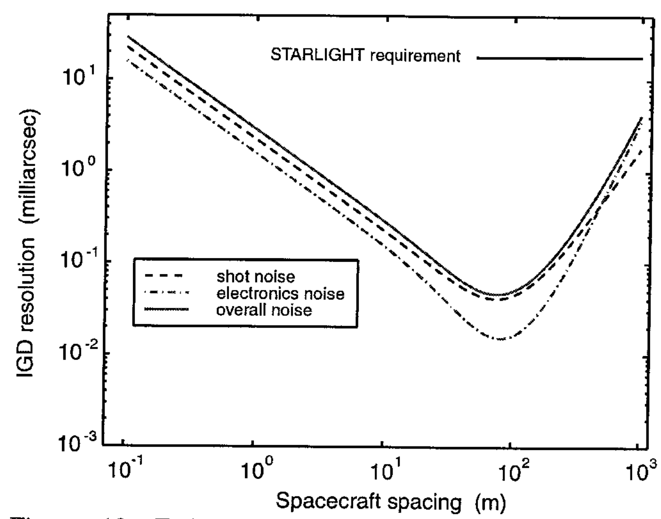


Figure 13. Estimate of sensor resolution, limited by electronics and shot noise.

6. CONCLUSIONS

We have implemented and demonstrated on the ground a metrology system for NASA's *StarLight* mission, a first space-based separated-spacecraft stellar interferometer. The system consists of a novel dual-target linear system and angular metrology for maintaining the pointing. The components and integration techniques needed to implement the system in space are currently being developed.

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